THE ASTROPHYSICAL JOURNAL, 545:753–757, 2000 December 20

GAS FUELING AND NUCLEAR GASEOUS DISK FORMATION IN MERGING BETWEEN A CENTRAL MASSIVE BLACK HOLE AND A GAS CLUMP

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Received 2000 June 19; accepted 2000 August 7

ABSTRACT

We numerically investigate dynamical evolution of a merger between a central massive black hole (MBH) and a gas clump with a mass of 10^6–10^7 $M_\odot$ in the central tens of parsecs of a galactic bulge. We found that the strong tidal gravitational field of the MBH transforms the initial spherical clump into a moderately thick gaseous disk (or torus) around the MBH. The developed disk is also found to show rotation, essentially because the tidal field changes efficiently the orbital angular momentum of the clump into intrinsic angular momentum of the disk. Furthermore, about a few percent of the gas mass (corresponding to a few 10^5 $M_\odot$) in the clump is found to be transferred to the central subparsec region around the MBH within an order of 10^6 yr. We thus suggest that successive merging of gas clumps onto an MBH can not only be associated closely with the formation of the nuclear disk around the MBH but also can provide gas fuel for the MBH.

Subject headings: galaxies: active — galaxies: evolution — galaxies: kinematics and dynamics — galaxies: nuclei

1. INTRODUCTION

It is one of the long-standing and remarkable problems in the formation and evolution of active galactic nuclei (AGNs) how interstellar gas can be fueled to the central massive black hole (hereafter referred to as MBH) in galaxies (e.g., Shlosman, Frank, & Begelman 1989; Shlosman, Begelman, & Frank 1990). The central core of this fueling problem is in how the angular momentum of interstellar gas can be reduced by more than several orders of magnitude such that the gas can be transferred into the central subparsec of a galaxy (Shlosman et al. 1990). Shlosman et al. (1989) proposed the so-called "bars within bars scheme" as a possible mechanism for fueling AGNs. They showed analytically that for suitable conditions the gas inflow induced by bar instability again produces the self-gravitating disk in a smaller region and a new small bar develops, which induces further gas inflow. Friedli & Martinet (1993) numerically studied the dynamical evolution of doubly nested bars and found that for suitable conditions the gas inflow to the nuclear region is derived by the dissolution of the secondary smaller bar in a two-bar system. Bekki & Noguchi (1994) found that dynamical heating by two sinking cores and subsequent dissipative cloud-cloud collisions in a merger can drive a larger fraction of gas to the central 10 pc. These theoretical studies essentially stressed the importance of nonaxisymmetric and time-dependent gravitational potential in gaseous inflow into the central subparsec regions.

Shlosman & Noguchi (1993) presented an alternative and important point of view that for a strongly self-gravitating disk, gas clumps formed from local gravitational instability can quickly fall toward the nuclear region around the MBH owing to dynamical friction. Noguchi (1998), furthermore, demonstrated that these massive clumps are more likely to be formed in the early disk formation phase when disk galaxies have a larger amount of gas. These two numerical studies stressed the importance of discrete gas clumps (not continuous and diffuse gas) in gas fueling processes. Recent observational studies of ultraluminous infrared galaxies (ULIRGs), some of which are suggested to contain MBHs (Sanders et al. 1988), have revealed that most ULIRGs show compact blue knots that are probably very young star clutters with masses of 10^5–10^9 $M_\odot$ (e.g., Surace et al 1998). Shaya et al. (1994), furthermore, revealed a number of bright and possibly young star clusters in the core of ULIRG Arp 220 and suggested that these clusters can be very quickly transferred to the inner tens of parsecs within an order of 10^8 yr owing to dynamical friction. Since these observed clusters could be formed by massive gaseous clumps (e.g., massive molecular clouds), the above observational results lead us to suggest that gaseous clumps are also transferred to the vicinity of MBHs.

The purpose of this paper is to investigate numerically merging between a central massive black hole with a mass of $\sim 10^7$ $M_\odot$ and a spherical gaseous clump with a mass of $\sim 10^7$ $M_\odot$ and a size of ~ 10 pc. We demonstrate that the strong tidal field of the MBH can transform the clump into a moderately thick gaseous disk (or torus): the MBH can form the surrounding nuclear disk for itself. We suggest that the viscosity of the gaseous disk could transfer the gas, furthermore, to the vicinity of the MBH and cause the MBH to grow. Based on the present numerical results, we provide several implications for recent observational results, such as the origin of the nuclear gaseous torus considered to be ubiquitous in Seyfert 2 galaxies (e.g., Krolik & Begelman 1986; Antonucci 1993), active star formation around the MBH in the Galaxy (e.g., Morris & Serabyn 1996), apparently double M31 nuclei (e.g., Kormendy & Bender 1999), and nuclear gaseous disks observed in some galaxies such as NGC 4261 (e.g., Jaffe et al. 1993). The importance of tidal disruption of stars passing by a central MBH in the accretion disk was already suggested by Gurzadyan & Ozernoy (1979), and there are several numerical studies investigating tidal disruption of *star* clusters (e.g., Charlton & Laguna 1995; Emsellem & Combes 1997; Bekki 2000). However, it is highly uncertain how a merger between an MBH and a massive *gas* clump dynamically evolves. Thus, we believe that the present study not only presents a solution to the fueling problem of AGNs but also provides a clue to the origin of the nuclear structure of galaxies.

2. MODEL

We consider a merger between a central MBH with a mass of $M_{\rm BH}$ and a gaseous clump with a mass of $M_{\rm gas}$ and a size of R_t in the central region of a galactic bulge. From now on, all masses and lengths are measured in units of $M_{\rm BH}$ and R_t, respectively, unless specified. Velocity and time are measured in units of $v = (GM_{\rm BH}/R_t)^{1/2}$ and $t_{\rm dyn} = (R_t^3/GM_{\rm BH})^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_{\rm BH} = 10^7$ (10^8) $M_\odot$ and $R_t = 10$ pc as a fiducial value, then $v = 6.5 \times 10$ (2.1×10^2) km s^{-1} and $t_{\rm dyn} = 1.49 \times 10^5$ (4.72×10^4) yr, respectively. Both the MBH and the clump are assumed to feel the external gravitational field of the bulge component. The MBH is assumed to be initially located at the center of the bulge, and the initial separation between the MBH and the clump is set to be $3R_t$. For the radial density profile of the bulge, we adopt the universal profile proposed by Navarro, Frenk, & White (1996). We assume that the scale length is equal to $10R_t$ and determine the central density such that the total mass of the bulge within $200R_t$ ($\sim$2 kpc) is $200M_{\rm BH}$. The adopted ratio of the bulge mass to the MBH one is well within a reasonable value derived by Faber et al. (1997). The total mass of the bulge within $R = 1.0$ (the central 10 pc), where R is the distance from the center of the bulge, is hereafter represented by $M_{\rm gal}$. We model an $n = 1$ polytropic gas sphere in hydrostatic equilibrium for the initial density profile of the clump. For the fiducial model, the mass ratios $M_{\rm gas}/M_{\rm BH}$ and $M_{\rm gal}/M_{\rm BH}$ are set to be 1.0 and 0.3, respectively. For this case, the tidal radius of the MBH is nearly the same as the size of the clump.

We describe the gaseous nature of the clump by using the smoothed particle hydrodynamics (SPH) method (introduced by Lucy 1977 and Gingold & Monaghan 1977), in which the fluid is modeled as a collection of fluid elements. We use a spherically symmetric spline kernel and variable smoothing length to treat the huge density contrast. An artificial viscosity is introduced in the SPH method to treat shocks accurately (Monaghan & Gingold 1983). We use the form given by equation (2.25) of Hernquist & Katz (1989) with $\alpha = 0.5$ and $\beta = 1.0$. The gas clump is assumed to be polytropic gas with the equation of state represented by $P = K\rho^\gamma$, where P, K, ρ, and γ are pressure, constant, density, and the ratio of specific heat (2 for the adopted value of $n = 1$ polytrope), respectively. Accordingly, radiative cooling processes, which can be very important for the evolution of gas clumps, are not included in the present paper. The gravitational interaction between SPH gas particles is computed by a hierarchical TREE method (introduced by Barnes & Hut 1986). The code we have used in this study is nearly the same as that used in Bekki (1995). The TREESPH code used by Bekki (1995) is a modified version of the one used by Heller & Shlosman (1994).

The initial orbital plane of the merger is assumed to be exactly the same as the x-y plane. The initial x and y position (x, y) is set to be (0, 0) for the MBH and (3, 0) for the clump in all models. Initial x and y velocity (V_x, V_y) is set to be (0, 0) for the MBH and (0, $0.75V_{\rm cir}$) for the clump in the fiducial model, where $V_{\rm cir}$ is the circular velocity at the initial position of the clump. The number of particles for the clump is 5000, and the parameter of gravitational softening is set to be fixed at 2.97×10^{-2} in our units for all the simulations. By using the TREESPH code originally proposed by Hernquist & Katz (1989), we carry out all the calculations related to the above dynamical evolution of mergers. Using the above model, we mainly describe morphological, structural, and kinematical properties of the merger remnant in the fiducial model. Moreover, we summarize briefly the dependence of mass distribution of the merger remnant on the initial merger parameters such as $M_{\rm BH}$, V_x, and V_y. More details on the parameter dependences will be described in our future papers.

3. RESULT

Figure 1 shows the time evolution of the mass distribution of a gaseous clump in the fiducial merger model. As the clump becomes close to the MBH, the strong tidal gravitational field draws out the clump, and consequently, the outer part of the clump winds itself round the MBH ($T = 6$). During this strong tidal disruption, angular momentum redistribution of the merger proceeds very effi-

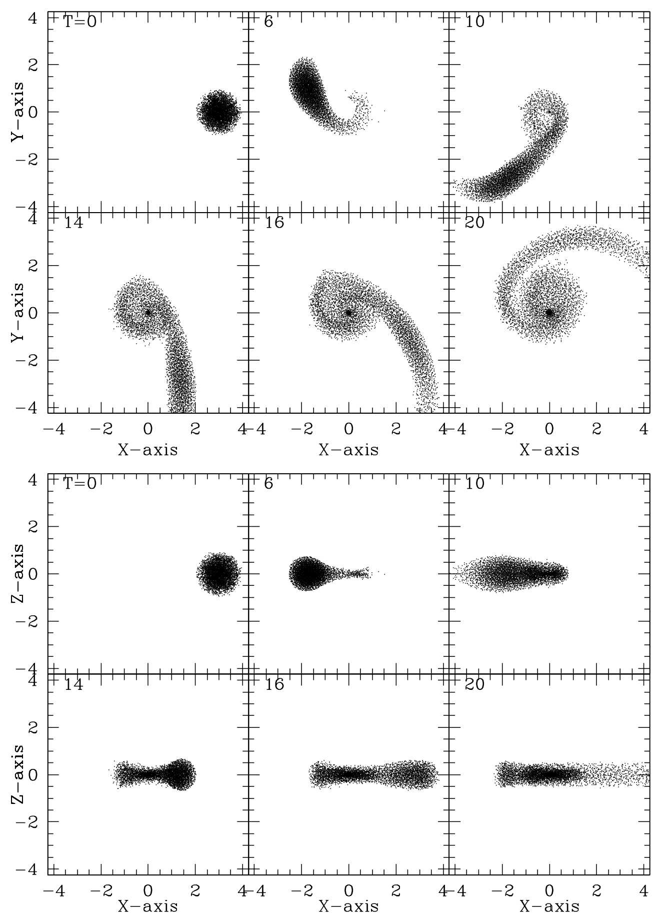

FIG. 1.—Mass distribution of a merger between the central MBH and a gaseous clump projected onto x-y plane (*upper six panels*) and onto x-z one (*lower six panels*) at each time T for the fiducial model with $M_{\rm gas}/M_{\rm BH} = 1.0$, $M_{\rm gal}/M_{\rm BH} = 0.3$, $V_x = 0$, and $V_y = 0.75V_{\rm cir}$. T (in our units) is indicated in upper left-hand corner of each panel. The MBH is initially located exactly in the center of a bulge component [i.e., the x and y position (x, y) is (0, 0)]. Here the scale is given in our units (corresponding to 10 pc), and each of the 12 frames measures 80 pc (8.5 length units) on a side. Note that the strong tidal field of the MBH transforms the initial spherical shape of the clump into a moderately thick nuclear gaseous disk.

ciently, and consequently a gaseous tidal tail is formed ($T = 10$ and 14). The MBH's tidal field finally transforms the initially spherical shape of the clump into a moderately thick gaseous disk with a remarkable tidal tail after merging ($T = 16$ and 20). During this morphological transformation, the initial orbital angular momentum of the clump is efficiently changed into the intrinsic angular momentum of the forming disk around the MBH. As a natural result of this, the developed disk clearly shows rotation. The vertical scale height of the developed disk depends mainly on the initial half-mass radius of the clump (for the present polytropic gas model).

As is shown in Figure 2, the developed nuclear gaseous disk clearly shows strong asymmetry both in surface density profile and in rotation curve along the x- and y-axes owing to the presence of one tidal arm. The radial density profile has a flat peak around $-0.4 < x\ (y) < 0$, where some fraction of gas is accumulated in the vicinity of the MBH. Owing to the self-gravity of the developed disk and the bulge's gravitational field (and the asymmetric mass distribution), the disk does not so clearly show the Keplerian rotation profile, though the gravitational field of the point mass is rather strong. As merging proceeds, the gas of the clump can be efficiently accumulated around the MBH (see Fig. 3). The gas mass within $R = 0.1$ in our units (corresponding to 1 pc), where R is the distance from the MBH, rapidly increases at $T = 8$ and finally amounts to ~ 0.04 in our units (corresponding to $4 \times 10^5\ M_\odot$) at $T = 20$. This result implies that merging between an MBH and a gas clump can very efficiently transfer gas to the surrounding of the MBH and consequently form an AGN: an MBH can provide gaseous fuel for itself because of its strong tidal gravitational field.

The vertical structure is dynamically supported by the pressure gradient of the developed gas disk. Since an $n = 1$ polytropic gas sphere is assumed in the present model, this means that the disk is dynamically supported by the gaseous density gradient. Initial mean gaseous density of the spherical clump is rather high ($2.39 \times 10^3\ M_\odot\ \mathrm{pc}^{-3}$), and consequently, the mean surface density of the developed gas disk (after merging) is also rather high ($7.96 \times 10^5\ M_\odot\ \mathrm{pc}^{-2}$). Thus, radiative cooling could be very important for further evolution of the gaseous disk (and for long-term evolution of the disk). However, the present model does not include cooling processes owing to the adopted assumption of the $n = 1$ polytropic gas sphere. The present study therefore cannot discuss the physical roles of gaseous cooling in dynamical evolution of the developed gaseous disk. The disk in the present model is dynamically stable and exists for a very long timescale (more than 10^8 yr) owing to our not having included the radiative cooling. The vertical scale length of the disk (or torus) depends on the initial size of the clump (for the present case, less than 10 pc). The disk formed by tidal disruption of the MBH is discussed later in terms of the nuclear gaseous torus that is believed to be ubiquitous in Seyfert 2 nuclei.

It depends mainly on the mass ratio of $M_{\mathrm{gas}}/M_{\mathrm{BH}}$ whether or not a nuclear disk around an MBH is formed after merging (and tidal interaction). As is shown in Figure 4, the gas clump is only slightly distorted by the tidal gravitational field of the MBH for the model with larger $M_{\mathrm{gas}}/M_{\mathrm{BH}}$ (i.e., smaller M_{BH} and weaker tidal field of the MBH) such that no disks can be formed. For the model with smaller

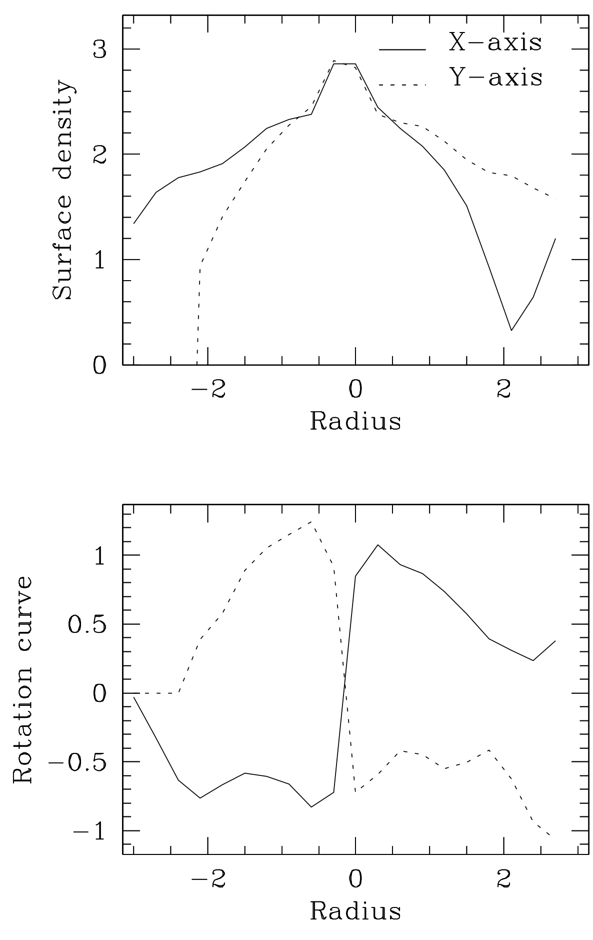

FIG. 2.—Radial density profile (*upper panel*) and rotation curve (*lower panel*) along x-axis (*solid line*) and y-axis (*dotted line*) at $T = 20.0$ for the developed nuclear disk. Here the scale for length and velocity is given in our units and the surface density scale is given in units of $100 \times M_{\mathrm{BH}}/R_t^2$ for clarity. Note that since the initial orbital angular momentum of the merger is efficiently changed into the intrinsic angular momentum of the disk, the disk shows rotation clearly. Note also that structure and kinematics of the disk clearly show asymmetry in the radial distributions owing to the one tidal arm formed during merging.

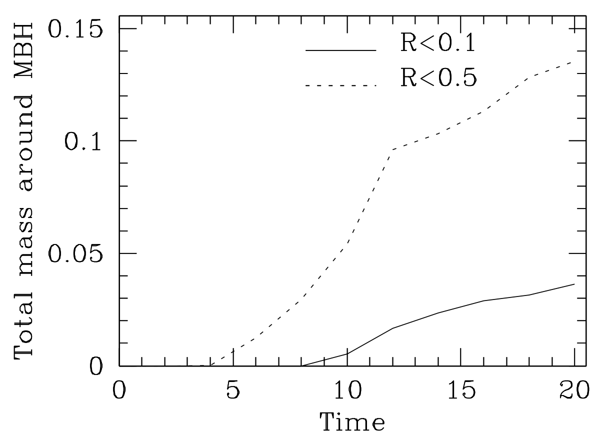

FIG. 3.—Time evolution of gas mass accumulated within $R = 0.1$ (*solid line*) and 0.5 (*dotted line*), where R is the distance from the MBH. Accumulated mass is 0.14 for $R < 0.5$ and 0.04 for $R < 0.1$. Gas fueling rate in this model for $10 \leq T \leq 20$ is estimated to be $\sim 2.7\ M_\odot\ \mathrm{yr}^{-1}$ for $R < 0.1$ (the central 1 pc). Thus, this figure indicates that merging between an MBH and a gas clump can be a possible candidate for ideal fueling mechanisms.

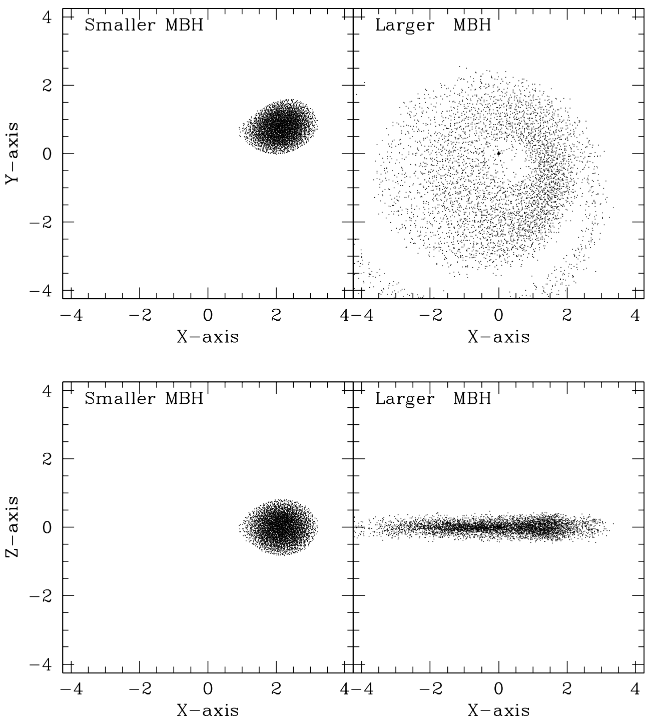

FIG. 4.—Final mass distribution projected onto *x*-*y* plane (*upper two panels*) and onto *x*-*z* one (*lower two panels*) for the model with $M_{\rm BH} = 0.1$, $M_{\rm gas}/M_{\rm BH} = 10.0$, and $M_{\rm gal}/M_{\rm BH} = 3.0$ (*left panels*, represented by "Smaller MBH") and for the model with $M_{\rm BH} = 10.0$, $M_{\rm gas}/M_{\rm BH} = 0.1$, and $M_{\rm gal}/M_{\rm BH} = 0.3$ (*right panels*, represented by "Larger MBH"). Here parameter values other than those specified above are exactly the same as those of the fiducial model for each of the two models. Note that only for larger MBH model, a moderately thick gaseous torus (or a disk with a central hole) is formed around MBH.

$M_{\rm gas}/M_{\rm BH}$ (i.e., larger $M_{\rm BH}$), on the other hand, the spherical shape of the clump is finally transformed into a moderately thick torus (or a disk with a central hole) around the MBH. Furthermore, the morphology of the central gaseous structure depends on the present model parameters. In the model with rather small initial angular momentum ($V_x = 0.0$ and $V_y = 0.2V_{\rm cir}$), the clump merges with the MBH to form a spherical clump with the MBH gravitationally trapped in the central region of the clump (i.e., no tidal disruption of the clump). A larger eccentric gaseous disk with a steeper radial density profile is formed in the model with larger initial orbital angular momentum ($V_x = -0.5V_{\rm cir}$ and $V_y = 0.75V_{\rm cir}$). Only a considerably small gaseous disk around the MBH is formed owing to gas transfer in the model in which the MBH and the clump come together in a hyperbolic way ($V_x = -2.0V_{\rm cir}$ and $V_y = 0.75V_{\rm cir}$). These dependences imply that nuclear gaseous structure around an MBH in a galaxy is determined by the orbital parameters of a merger and the mass of the MBH.

4. DISCUSSION

We have performed numerical simulations of merging between an MBH and a gas clump in the central region (~ 10 pc) of a bulge. Although the present model (in particular, the detailed gaseous dynamics) is very idealized, less realistic, and oversimplified in some points, we believe that the idealized model taken here can provide important implications for the nature of the nuclear regions of galaxies. We here discuss the following three points concerning the structure and activity of galactic nuclei.

4.1. *Formation of Nuclear Gaseous Disks*

Recently, *Hubble Space Telescope* (*HST*) observations have revealed nuclear gaseous disks with sizes ranging from ~ 1 pc to ~ 1 kpc in nearby galaxies (e.g., Jaffe et al. 1993, 1999). Our results suggest, first, that not the continuous gaseous inflow but the successive and sporadic merging of discrete gas clumps (or gas-rich small dwarf galaxies) onto an MBH can be one of the essentially important and basic processes of the observed nuclear gaseous disk formation. If the nuclear disk is really formed by such merging, what are the promising candidates for gas clumps reaching the vicinity of an MBH and how long does it take for the clumps to reach the central 10 pc around the MBH? On the first question, we suggest that massive gaseous clouds developed in gas-rich disks owing to local gravitational instability are the most promising candidates for the clumps that can reach the vicinity of an MBH. Shlosman & Noguchi (1993) found that if the gas mass fraction of a globally unstable disk is larger than 0.1, massive gas clumps (with masses of $\sim 10^7\ M_\odot$) formed from local gravitational instability can be transferred into the central inner kiloparsec owing to dynamical friction. Noguchi (1998), furthermore, demonstrated that these massive clumps are more likely to be formed in the early disk formation phase when disk galaxies have a larger amount of gas. These numerical results combined with the present one thus imply that the formation of gas clumps due to local gravitational instability in a gas-rich disk can be closely associated with merging between an MBH and a gas clump in the nuclear region of a galaxy (essentially because dynamical friction is very effective for such massive gas clumps).

On the second question, the timescale in which a gas clump can reach the central 10 pc around an MBH can be estimated by using a formula for dynamical friction (e.g., Binney & Tremaine 1987). Shaya et al. (1994) estimated the dynamical friction timescale ($T_{\rm fric}$) of a system located in the nuclear regions of a bulge as follows:

$$T_{\rm fric} = 3.9 \times 10^7 (r_i/500\ {\rm pc})^2 \times (V_c/400\ {\rm km\ s^{-1}})(10^8\ M_\odot/M_{\rm cl})\ {\rm yr}. \quad (1)$$

Here we neglected the term $\ln \Lambda$ (~ 6.6 for a plausible set of parameters), and r_i, V_c, and $M_{\rm cl}$ are the initial radius (from the MBH), circular velocity, and mass of the clump, respectively. The above estimation implies that a gaseous clump formed in the central about a few hundred parsecs of a gas-rich disk galaxy can be transferred to the vicinity of an MBH within $\sim 10^8$ yr. This accordingly suggests that a nuclear gas disk can grow very rapidly (within an order of $\sim 10^8$ yr) owing to sporadic inner transfer of gas clumps.

4.2. *A New Fueling Process ?*

Second, our results provide a more detailed description of gas fueling from the central 10 pc to the subparsec around MBHs. One of the remaining questions of the so-called fueling problem is the formation process of a massive accretion gas disk around an MBH. The present model provides a formation process of a gaseous disk with a size of ~ 10 pc; this disk could be associated closely, furthermore, with the formation of a subparsec-sized accretion disk around an MBH. After the formation of a nuclear disk with a size of

~ 10 pc due to merging between an MBH and a gas clump, the gas in the disk can be transferred to the vicinity of the MBH within a viscosity timescale of 10^6 yr (e.g., Shlosman et al. 1989; Jaffe et al. 1999). Even if an MBH is not so large as to tidally disrupt a clump (for the present model with smaller M_{BH}), the MBH trapped within the central high-density core of the clump could grow owing to Bondi-type (Bondi 1952) accretion. We accordingly point out that the merging could provide ideal gas fueling for MBHs. We suggest, furthermore, that since gas clumps are more likely to be formed and transferred to the nuclear regions in higher redshift galaxies (Noguchi 1998), MBHs can more rapidly grow owing to gaseous accretion and consequently show more pronounced nuclear activities at higher redshift.

The present model (with larger M_{BH}) showing the formation of the gas torus implies that the obscuring torus proposed for explaining the origin of the dichotomy between Seyfert 1 and 2 galaxies in the unified model (e.g., Krolik & Begelman 1986; Antonucci 1993) could be associated with merging between an MBH and gas clumps. The present model provides the following three predictions about the nature of Seyfert 2 galaxies, if the Seyfert types in a disk galaxy can be determined by whether or not there is an obscuring torus around an MBH in the disk. First, the present study predicts that late-type disk galaxies are more likely to show Seyfert 2–type activities with a possible obscuring torus. This is essentially because gas-rich clumps are more likely to be formed in gas-rich disks with a gas fraction larger than 0.1 (Shlosman & Noguchi 1993). Second, it does not necessarily depend on the global structure of a disk galaxy whether the disk shows Seyfert 1–type activity or Seyfert 2. As is shown in the present study, the most important factor for the formation of the nuclear torus is whether or not an MBH can come together with a gas clump. Therefore, considering that the formation of gas clumps is closely associated with local gravitational instability rather than global instabilities (that determine the global structure of galaxies), there should be no strong correlation between the global structure of galaxies and the type of AGN. Third, higher redshift galaxies are more likely to show type 2 Seyfert activities, since these are more gas-rich and consequently suffer from local gravitational instability that leads to gas clump formation.

4.3. *Evolution of Nuclear Structure in Galactic Bulges*

Third, the present model implies that if star formation is included and assumed to be dependent on gaseous density, high-density regions of the developed nuclear disk around the MBH can efficiently form stars: "mini-starburst" is triggered by merging between MBHs and gas clumps. We suggest, furthermore, that a young central cluster of blue stars observed in the very center of the Galaxy (e.g., Morris & Serabyn 1996) is a fossil record of the past merging event. Such mini-starburst could also contribute to the formation of nuclear-dense stellar systems that are considered to be associated closely with the growth of seed central black holes (e.g., Williams & Perry 1994). Furthermore, the present study provides a new clue to the origin of the M31 nucleus having two distinct brightness peaks with a separation of ~ 2 pc (see Kormendy & Bender 1999 for recent high-resolution observational results). Although Tremaine (1995) recently proposed a new idea that M31's nucleus is actually a single thick eccentric disk (with a mass of the order of $10^6\ M_\odot$) surrounding the central MBH, it is highly unclear how the disk was formed. Our results imply that if a smaller gaseous clump with a mass of $\sim 10^6$ merges with the MBH and if the later star formation transforms the formed gaseous disk into the stellar one, the proposed M31 eccentric disk is formed. (On this point, Bekki 2000 has already presented an alternative idea on M31's nucleus formation). Although some of the above several suggestions could be somewhat of an overinterpretation of the present numerical results, we lastly stress that merging between an MBH and gas clumps can be an important driver of nucleus evolution in galaxies.

We are grateful to the anonymous referee for valuable comments, which help to improve the present paper.

REFERENCES

Antonucci, R. 1993, ARA&A, 31, 473
Barnes, J., & Hut, P. 1986, Nature, 324, 446
Bekki, K. 1995, MNRAS, 276, 9
———. 2000, ApJ, 540, L79
Bekki, K., & Noguchi, M. 1994, A&A, 290, 7
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
Bondi, H. 1952, MNRAS, 112, 195
Charlton, J. C., & Laguna, P. 1995, ApJ, 444, 193
Emsellem, E., & Combes, F. 1997, A&A, 323, 674
Faber, S. M., et al. 1997, AJ, 114, 1771
Friedli, D., & Martinet, L. 1993, A&A, 277, 27
Gingold, R. A., & Monaghan, J. J. 1977, MNRAS, 181, 375
Gurzadyan, V. G., & Ozernoy, L. M. 1979, Nature, 280, 214
Heller, C. H., & Shlosman, I. 1994, ApJ, 424, 84
Hernquist, L. E., & Katz, N. 1989, ApJS, 70, 419
Jaffe, W., Ford, H. C., Ferrarese, L., van den Bosch, F., & O'Connell, R. W. 1993, Nature, 364, 213
Jaffe, W., Ford, H. C., Tsvetanov, Z., Ferrarese, L., & Dressel, L. 1999, in ASP Conf. Ser. 182, Galaxy Dynamics, ed. D. Merritt, J. A. Sellwood, & M. Valluri (San Francisco: ASP), 13
Kormendy, J., & Bender, R. 1999, ApJ, 522, 772
Krolik, J. H., & Begelman, M. C. 1986, ApJ, 308, L55
Lucy, L. 1977, AJ, 82, 1013
Monaghan, J. J., & Gingold, R. A. 1983, J. Comput. Phys., 52, 374
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Noguchi, M. 1998, Nature, 392, 253
Sanders, D. B., Soifer, B. T., Elias, J. H., Modore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74
Shaya, E. J., Dowling, D. M., Currie, D. G., Faber, S. M., & Groth, E. J. 1994, AJ, 107, 1675
Shlosman, I., Begelman, M. C., & Frank, J. 1990, Nature, 345, 679
Shlosman, I., Frank, J., & Begelman, M. C. 1989, Nature, 338, 45
Shlosman, I., & Noguchi, M. 1993, ApJ, 414, 474
Surace, J. A., Sanders, D., Vacca, W. D., Veilleux, A., & Mazzarella, J. M. 1998, ApJ, 492, 116
Tremaine, S. 1995, AJ, 110, 628
Williams, R. J. R., & Perry, J. J. 1994, MNRAS, 269, 538